Designing Digital Materials with Volumetric Gradients

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ABSTRACT

Next-generation engineering designs could be digitally conceived as vast constellations of material dots in space and physically fabricated with advanced Additive Manufacturing (AM) technologies. AM is already transforming how we create physical objects across a wide range of manufacturing industries. However, recent advances in multi-material AM make it possible to envision a form of three-dimensional pointillism, whereby complex structures are designed and assembled on a micron-by-micron basis through the precise placement of different material "dots" within three-dimensional space. In line with traditional pointillism techniques, different compositions of many small dots would collectively give rise to higher-level properties such as colour and geometry, but also *physical* properties such as: topology, stiffness, flexibility, and transparency. This paper first describes exciting challenges and opportunities associated with designing multi-material objects as constellations of material dots, then outlines initial experiments which explore data-driven volumetric gradients to design and fabricate physical objects using advanced PolyJet technologies.

Keywords: Functionally graded materials, digital materials, multi-material additive manufacturing, voxel print, computational design

1. INTRODUCTION

Recent advances in multi-material AM are enabling designers and engineers to create highly complex physical structures ranging from creative applications in fashion, sculpture, and consumer products to high-value areas such as aerospace, automotive and medical [1-5]. However, there are there are still significant challenges relating to how we digitally model designs for AM. Specifically, as advanced AM technologies make it possible to manufacture designs with increasing levels of geometric and material complexity, the question of how to best parameterise and represent these designs in ways which are computationally efficient becomes of critical importance. For example, Stratasys' PolyJet technologies make it possible to describe complex structures with a layer height of only 14 microns. However this means that traditional point-by-point parameterisations of 3D designs (as polygon or voxel models) become problematic for three key reasons [4-5].

Firstly, the computational expense of storing and sharing large CAD files with potentially billions of degrees-of-freedom is a major challenge area. Secondly, 3D designs which incorporate huge numbers of parameters are extremely difficult to control for designers and engineers. Finally, optimisation processes typically perform worse as the number of variable parameters increase, therefore point-by-point parameterisations cause serious challenges for discovering high-performance solutions with multi-material AM.

This paper presents a voxel-based approach to representing complex multi-material AM designs in ways which precisely address these three problem areas. The paper is structured as follows: first we present our approach which is based on a process of probabilistic material deposition that is guided by volumetric gradient patterns; second, we present initial results with printed multi-material structures; and finally, we conclude with a summary and discussion of exciting avenues for further research.

2. METHODS

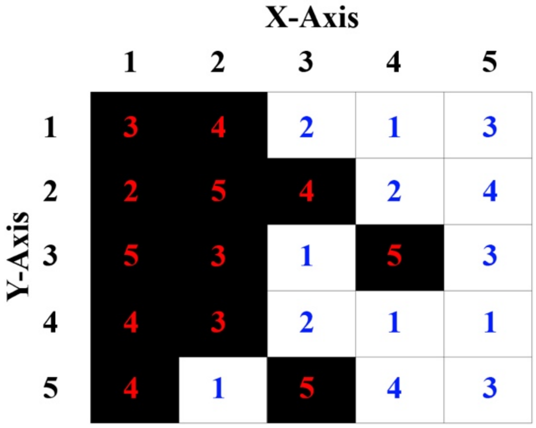
We now present a novel method of describing *Functionally Graded Materials* (FGM) for AM using volumetric gradient patterns to drive a probabilistic material deposition process. The key benefits of this approach are: (a) complex multi-material designs can be described with compact and scalable digital encodings (using only *bytes* rather than *gigabytes* or *terabytes* to store model data); (b) Volumetric gradient patterns can be automatically generated and optimised to suit engineering design challenges by leveraging a state-of-the-art neuroevolution algorithm called NEAT [6]; (c) As will be shown in this paper, seamless material gradations can be specified throughout an object's volume and fabricated using Stratasys' PolyJet J750.

As described in the previous section, a major challenge for designing multi-material AM parts is how to describe 3D models that may be composed of trillions of individual dots of material. To avoid point-by-point parameterisations of complex designs (which scale badly), we describe the property of each material dot using a *Probabilistic Material Deposition* strategy, which is, in turn, controlled by *Volumetric Gradient Patterns*.

2.1 Probabilistic Material Deposition

Imagine a 5x5 grid, whereby each of the 2D grid cells can be assigned either a black or white material. In this example, the 25 grid cells represent one complete layer of a cube-shaped object which can be printed on the Stratasys PolyJet J750. In this example, it is possible for a designer to specify the property of each of the grid cell individually (i.e. only 25 degrees-of-freedom per layer). However, as the grid dimensions increase by several orders of magnitude, it becomes inefficient and computationally expensive to define the property of each grid cell on an individual basis. To solve this problem and simultaneously provide a method of specifying seamless material gradations for multi-material AM, we have developed an approach we term "Probabilistic Material Deposition" (PMD).

Figure 1 describes the basic PMD approach, whereby each grid cell within a 5x5 grid is specified probabilistically. As shown in Fig. 1, for each grid cell a random number between 1 and 5 is first generated, if this randomly generated number is greater than the x-coordinate of the grid cell: a black dot is deposited, if not: a white dot is deposited. For clarity, the 5x5 grid shown in Fig. 1, shows all of the random numbers generated in this process and pseudocode is also provided.



X-Axis

Y-Axis	1	2	3	4	5
1	3	4	2	1	3
2	2	5	4	2	4
3	5	3	1	5	3
4	4	3	2	1	1
5	4	1	5	4	3

PMD Pseudocode

```
for each grid cell:
    int rand = random(1,5);
    if(rand > x_coordinate_of_grid_cell):
        deposit_black_dot();
    else:
        deposit_white_dot();
```

Figure 1: Probabilistic Material Deposition (PMD)

There are two key benefits to the PMD approach. Firstly, the grid dimensions can be resized and a higher resolution material specification can be instantly generated. This ability to scale up and down instantly is possible because each cell (or pixel) within the grid is defined as a function of its x-coordinate (i.e. the entire design is controlled by one parameter). Secondly, because material is defined probabilistically in response to a random number generation process, the resulting specification is well suited to fabricating FGM (Fig. 2).

Figure 2: Resized material gradient produced by PMD

2.2 Volumetric Gradient Patterns

Figures 1 and 2 demonstrate the specification of material properties using a simple and linear probability gradient, whereby the material, *M*, that is deposited within each grid cell is defined as a function, *f*, of the grid cell's x-coordinate. Using different spatial functions, it is possible to describe a wide range of different gradient patterns using the same method (Fig. 3).

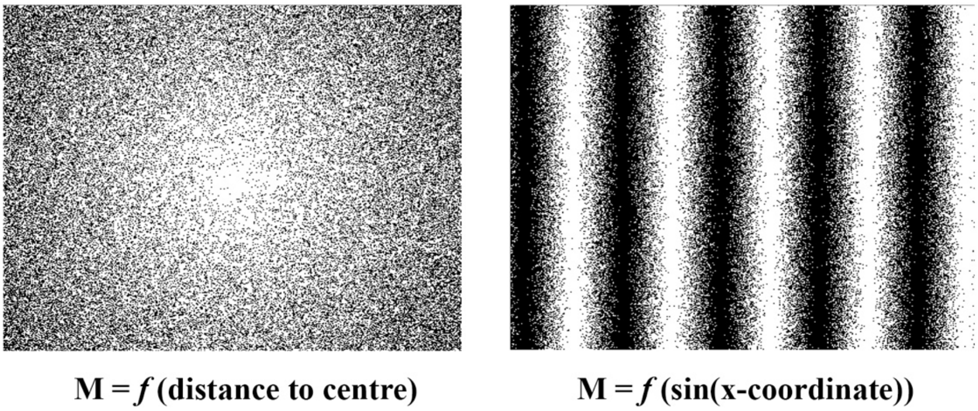


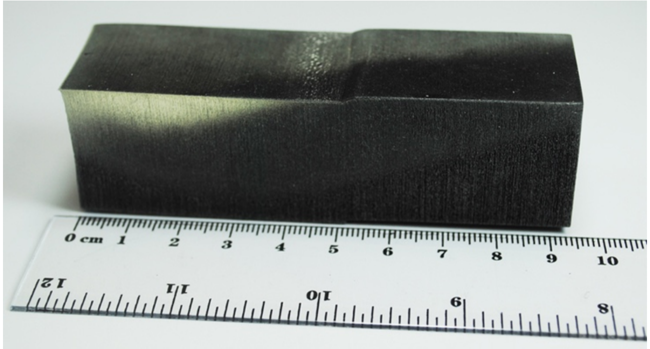
Figure 3: PMD driven by spatial functions

The gradient patterns shown in Figure 3 are based on 2D and 1D mathematical functions (i.e. distance to centre from point (x,y), and sine(x), respectfully). However, it is trivial to extend this method for three-dimensional (i.e. (x,y,z)) *volumetric gradient patterns*. For full details on defining and optimising volumetric gradient patterns for use within engineering design see [7-9].

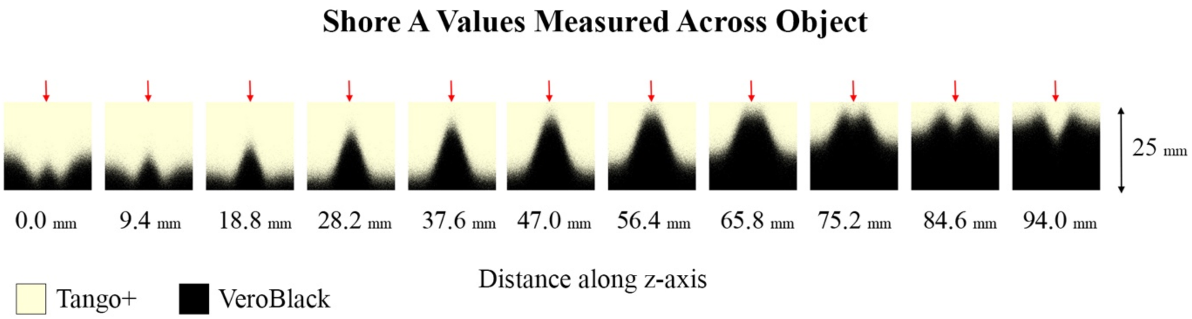
3. RESULTS

To test the physical properties of objects printed using our approach we perform two experiments. In the first experiment, we specify a simple volumetric gradient pattern and use this information to drive PMD of two different materials: *Tango+* which is a semi-clear and flexible material with a Shore A hardness value of 26-28, and *VeroBlack* a stiffer polymer with a Shore D hardness value of 83-86. The printed object is shown in Figure 4, and comprises over *700 million* individual dots of material.

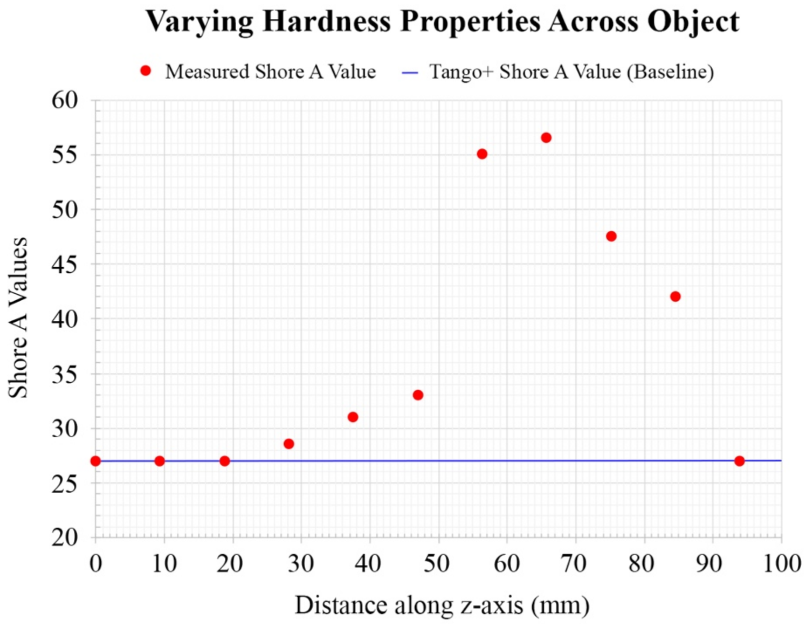
To test the physical properties of the material gradation, we used durometer to measure the Shore A values at set points along the length of the object (Fig. 5). As shown in Fig. 6, our findings show that we able to vary the hardness values of the material by blending discrete dots of Tango+ and VeroBlack at small scales (Fig. 7). Critically, the (on-computer) file size of the volumetric gradient used in this experiment is only 3kB, and because each slice of the model can be generated on a layer-by-layer basis via the PMD process, this approach has the potential to significantly reduce file sizes needed to model and fabricate complex multi-material AM parts in future manufacturing processes.



<u>Figure 4:</u> Photograph of printed FGM (defined via PMD. Materials: Tango+ and VeroBlack



<u>Figure 5:</u> Digital 2D slices of the FGM (slices taken along z-axis)



<u>Figure 6:</u> Shore A values measured at 11 points along FGM (as highlighted in Figure 4).

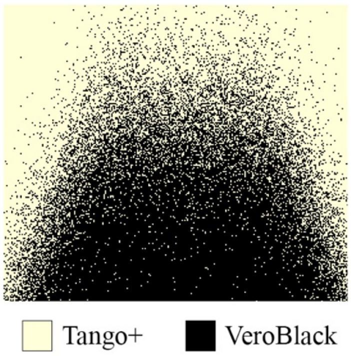


Figure 7: Close-up view of FGM (at point of Shore A value measurement at 65.8mm).

The second experiment uses a different volumetric gradient pattern to combine discrete dots of blue and yellow polymer (VeroCyan and VeroYellow). As shown in Figure 8, this experiment visually demonstrates how *low-level* design decisions, (i.e. the exact composition of blue and yellow dots), give rise to emergent *higher-level* product features, such as (the perception of) different shades of green.

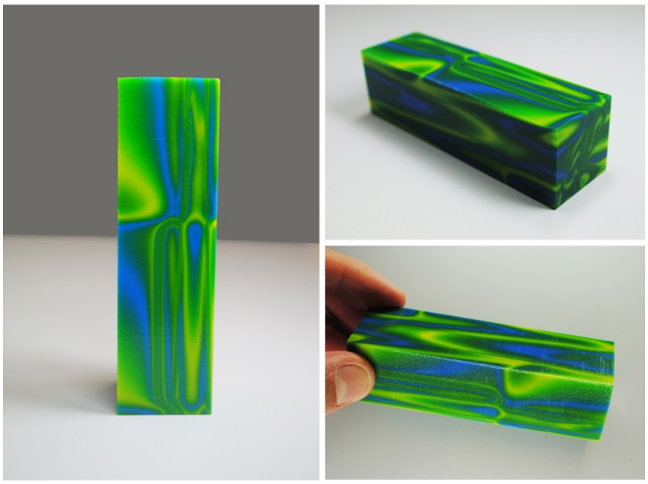


Figure 8: Blending VeroCyan and VeroYellow materials with PMD to create different colours

CONCLUSION

This paper describes an approach to describing *functionally graded materials*, using *volumetric gradient pattern*s that drive a process of *probabilistic material deposition*. Our initial results demonstrate that it is possible to vary material properties (i.e. hardness values) across a physical object, and control the blending of two base colours (i.e. blue and yellow) to produce a larger spectrum of different colours (i.e. greens). We describe that volumetric gradients can be expressed with minimal computational expense, and that our approach allows fabrication data to be output on a layer-by-layer basis, which theoretically eliminates the need to store complete material specifications during the fabrication process. Finally, as the author has demonstrated in previous works [7-9], volumetric gradient patterns can be automatically generated and optimised using a powerful algorithm called NEAT [6], which opens up exciting possibilities of creating high-performance multi-material AM parts in future work.

Further work is now needed to explore several areas. Firstly, the designs presented in this paper are limited to a Cartesian (x,y,z) volume, which makes it difficult to apply this method to existing geometries and/or work with existing CAD packages. Further work is required (and underway) to address this issue. Secondly, further work is needed to rigorously test material properties of multi-material structures beyond this proof-of-concept. Finally, in order to discover high-performance solutions with this approach it is essential to create new multi-scale methods of simulating the physical properties of complex multi-material parts. For example, it may be possible to exploit the probabilistic nature of this method to generate lower resolution voxel models which approximate physical properties within acceptable tolerances. However, further work in this area is needed.

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